Renewable and Sustainable Energy Reviews 15 (2011) 4310–4319

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain

D.L. Talavera*, E. Muñoz-Cerón, J. de la Casa, M.J. Ortega, G. Almonacid

IDEA Research Group (Investigación y Desarrollo de Energía Solar), University of Jaén, Campus las Lagunillas s/n, 23071 Jaén, Spain

ARTICLE INFO

Article history:
Received 6 April 2011
Accepted 5 July 2011
Available online 15 September 2011

Keywords:
Building integration
Grid-connected
Economic analysis
LCOE

ABSTRACT

The integration of grid-connected PV systems into buildings or public areas is one of the most usual applications of the photovoltaic solar energy in developed countries and it is being highly promoted by several European governments. In this paper it has been evaluated the photovoltaic potential of the Campus of the University of Jaén and it has been defined possible areas where the PV systems could be installed according to power requirements, space possibilities, the electrical configuration of the Campus and some social integration requirements too. The definition of the PV potential, together with a technical analysis for the calculation of the energy generated, is the previous step for carrying out an economic and cost analysis in order to certify the profitability of these systems in general, particularizing the study for the case of this University located in Southern Spain. The PV electricity cost generated has been calculated through the concept levelised cost of electricity (LCOE), where in our case is estimated to be around 0.13–0.14 € kWh^{-1}. The results obtained in this economic analysis recommend the implementation of PV grid-connected systems (PVGCS) as the internal rate of return reaches a maximum value of 6.21%, the net present value is positive and the discounted payback time is around 16 years. An additional sensitive analysis shows the influence that some parameters have on the LCOE, specially the initial investment, the energy yield and the nominal discount rate.

Contents

1. Introduction

The integration of grid-connected PV systems into buildings or public areas is one of the most usual applications of the photovoltaic solar energy in developed countries [1,2].

Moreover, in the Spanish legislative framework, with the application of the Royal Decree 1578/2008, it is recognized the benefits of Building Integrated Photovoltaic (BIPV) systems, not only because they do not increase the land occupation but the advantages of the distributed electricity generation as well as their contribution to a social spreading of renewable energies [3]. Apart from the promotion of BIPV systems in Spain, the main reason of this Decree was to rationalize the deployment of PV in Spain and to control the impact of the feed-in tariff in the national economic situation.

* Corresponding author. Tel.: +34 953 21 28 09; fax: +34 953 21 19 67.
E-mail address: dlopez@ujaen.es (D.L. Talavera).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.07.119

According to the previous law, the Royal Decree 661/2007 from 2007 [4], the RD 1578/2008 implied a 30% reduction of the feed-in tariff and further progressive cuts, which could reach 10% annually. Likewise, it established three installation types: type I.1: systems on top of buildings with a power limit of 20 kW; type I.2: systems on top of buildings with more than 20 kW of power and a limitation of 2 MW and type II: systems on undeveloped areas with a limitation of 10 MW. Also, it was established a power cap of 500 MW in 2009 and a similar one for the following two years. The feed-in tariffs approved for the first quarter of the year 2011, to be paid over 25 years, were: type I.1: 0.3135 € kWh^{-1}; type I.2: 0.2788 € kWh^{-1} and type II: 0.2517 € kWh^{-1}.

Lately, in September 2010 and due to the economic situation of the country, the Spanish feed-in tariff regime was modified for those systems not gathered in the 2011 first quarter registry. The Royal Decree 1565/2010, apart from further promoting PV systems integrated in buildings, either on façades or on top of roofs, implies an additional reduction in feed-in tariffs of 5% for installations of type I.1, 25% for type I.2 and 45% for type II [5].

The feed-in tariff for the projects that have been inscribed in the second quarter of the year 2011 is approximately of 0.2888 € kWh^{-1} for the small systems on roof, 0.2037 € kWh^{-1} for the type I.2 (above 20 kW) and 0.1345 € kWh^{-1} for systems installed on the ground [6].

Additionally, a new Royal Decree-law (RD 14/2010), from December 2010, limits the energy entitled to the feed-in tariff, as it fixes the number of hours of operation, according to the type of installation – fixed, one-axis and two-axis tracking – and the climatic zone established by the Spanish Building Technical Code law [7,8].

Therefore, prospective owners/investors are concerned for any further modification of the present regulatory framework, such as the financial incentives, the number of hours of operation and the years entitled to the feed-in tariff as it may affect the profitability and cost of the Photovoltaic Grid-Connected Systems investment, hence an economical and cost analysis of the PVGCS on buildings to ascertain the influence of the new regulatory framework on the PVGCS's profitability and cost is demanded.

In this paper it has been evaluated the photovoltaic potential of the Campus of the University of Jaén and it has been defined possible areas where the PV systems could be installed according to power and space requirements, the electrical configuration of the Campus and its social integration too. The analysis of the PV potential is the previous step to carry out a cost and economic analysis for implementing this photovoltaic grid-connected integration according to the new regulatory framework in Spain.

Because of the characteristics of the facilities of the Campus of the University, the PV systems will be installed on the building rooftops, parking lots or façades; therefore, the technical analysis will include a complex shading study. The methods for the economic analysis used in this paper are the net present value (*NPV*), the discounted payback time (*DPBT*) and the net internal rate of return (IRR_n). Regarding the cost analysis, it has been focused on the estimation of the electricity cost production through the concept: levelised cost of electricity (*LCOE*), so this result can be compared with other sources of electricity generation.

2. Technical analysis

The University of Jaén campus is the location chosen to carry out the technical analysis that will be used as base case to show the economical and costs results for PV grid-connected systems.

The campus (Fig. 1) is located in Southern Spain (37.73N and 3.67W) and the average annual radiation in this area is favourable for the installation of PV grid-connected systems, both in ground or building integrated.

The technical analysis starts from the identification of potential areas where the PVGCS ensure that the Spanish law is upheld among other aspects, and subsequently it is analyzed each area in order to study its profitability in energy terms.

2.1. Definition of potential PV locations

A first criterion to identify suitable areas for the PV systems is the grid-connection characteristics of the Campus, so an analysis of the electrical grid of the University will allow us to identify possible points of connection to the existing electrical grid.

The maximum power demand goes up to 3200 kW, while the annual consumption of electricity reaches around 6500 MWh. This energy is transferred by a local electrical grid made up of a high-voltage ring network that interconnects five transformer stations, which belong to the University, that supply low-voltage electricity to all the University facilities.



Fig. 1. Aerial picture of the University of Jaén Campus.

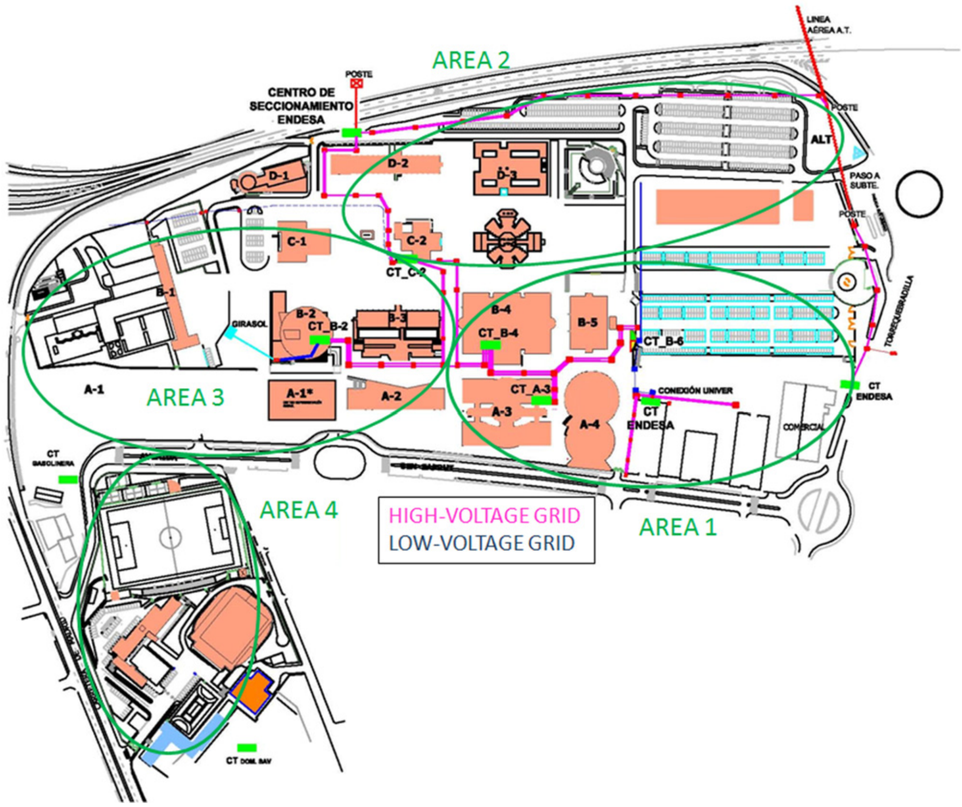


Fig. 2. Areas analyzed according to electrical determinants.

According to the Spanish law, it is compulsory to inject the energy generated in points out of the user's property, so the connection points mean a legal restriction that can limit the potential areas of photovoltaic interest. This is a determining factor in order to benefit from the feed-in tariff established in the Spanish regulatory framework.

After analyzing the distribution of the electrical grid and the locations of the transformer stations that are property of the University and those owned by the local Electricity Company, the Campus has been divided into four different PV potential areas, as it can be observed in Fig. 2.

The study of the electrical configuration of each area proposed has to be combined with space availability requirements, the usefulness of the selected zones besides taking into account the future urban development of the Campus.

A first approximation estimates that Area 3 has to be rejected in the short-term analysis, mainly because the PV electricity generated has to be used for self-consumption as it does not exist external connection points where the energy generated could be injected. Furthermore, it exits a great uncertainty related to the urban development in this area, as it will be the zone dedicated to the future expansion of the campus.

Among the locations defined, in a preliminary study Areas 1 and 4 are the most suitable places for this project because they have some eases for the evacuation of the electricity generated so, at first glance, these areas are more proper to set a PV system. In their proximity there are several transformer stations property of Sevillana-Endesa, the local Electricity Company, so it could be possible to connect the PV systems in low-voltage, facilitating the administrative procedure that the University must accomplish.

The evacuation of the electricity generated in Area 2 should be made in high-voltage because there are not transformer stations in its proximity. To inject the electricity generated by PV sources in high-voltage is an alternative possibility that is allowed in the Spanish laws.

It has been highlighted, through the help of satellite photography, all the feasible areas to install a PV system in the campus, as it is shown in Fig. 3. In this prior identification phase, it has been rejected those places where clearly it means a problem due to shadows or bad orientation and leaning. This satellite photography allows us to distribute, in a preliminary way, the modules on the surfaces of some of the locations.

2.2. Energy analysis of the selected areas

Once it has been defined the potential areas, an energy analysis of the selected zones it is suitable in order to calculate the electricity supplied by these PV systems.

This research has been carried out through the use of two different tools. First of all, the orthopicture tool has been used in order to obtain an accurate topographic uplifting of the buildings, parking lots, vegetation and other elements of the campus. This tool gathers under the same system real pictures (satellite images) with geometric properties similar to the one offered by traditional cartography, allowing us to measure angles and distances.

As noted in the previous section, it is necessary to study the shadows in a deeper way, so for this reason it is used a second tool, the so-called "PV-Syst™″ software, which is a commercial tool for the estimation of the electricity produced by PV systems. With the help of the orthopicture and the preliminary distribution of the PV modules, it is possible to design an accurate system that will be able to simulate and obtain the annual PV electricity generated by the system (E_{PV}), expressed in kWh year^{-1}, of a specific location.

The commercial software PV-Syst™ not only allows us a complete analysis of the PV potential, but it is also a powerful tool to recreate the scene of the buildings, the PV system and its surround-

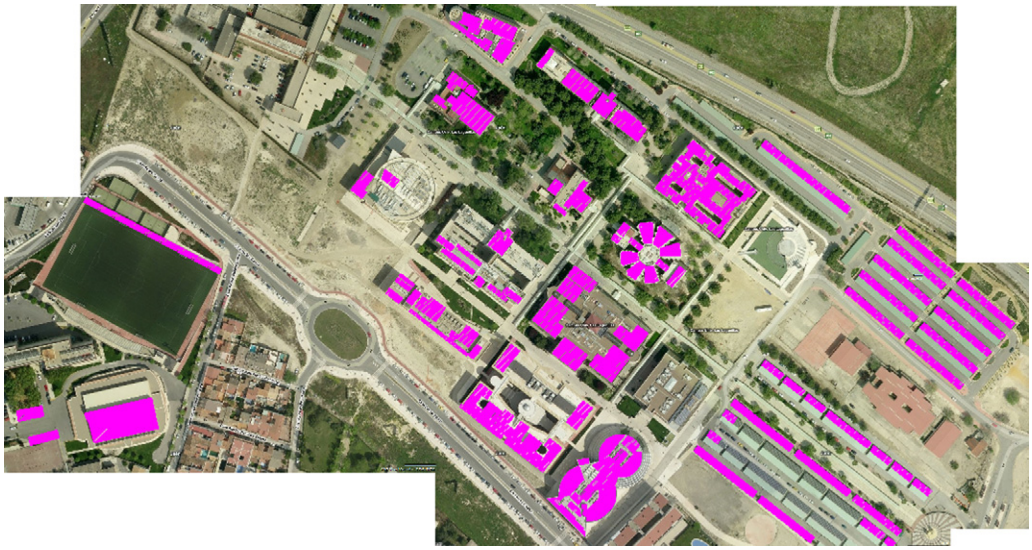


Fig. 3. Initial definitions of potential PV areas according to urban development limitations.

Bing™.

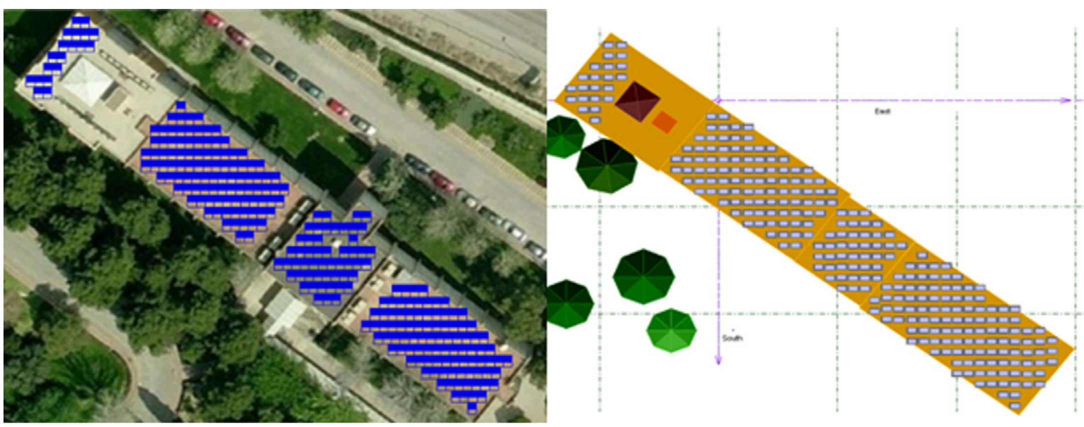


Fig. 4. Simulation with a professional software.

Bing™ and PV-Syst™.

ings too, as it is shown in Fig. 4. In this way, we can estimate the E_{PV} taking into account possible shades among them. The acquisition of the dimensions of the buildings and its real position, through the orthopicture tool, it has allowed us to deeply study the energy losses caused by different shadows (surroundings or self-shading).

The energy results obtained in the studies are gathered in Table 1, where it is shown the annual PV electricity yield (Y), expressed in kWh kWp^{-1} year^{-1}. With this data, and the power of each location it is possible to calculate the electricity generated by means of the future PV systems, which it will be approximately the 25% of the annual electricity consumption of the University. This data can convert the University of Jaén in an international referent and an example of how to accomplish the European Directive 2009/28/CE that settles that 20% of the electricity consumption in Europe has to be supplied by renewable energy sources by 2020 [9].

Areas 1 and 4 are the nearest places to the transformer stations of the Electricity Company. Firstly, the sport facilities located in Area 4 offers a wide extension to place different PV generators. The possible PV systems are only limited by the transformer stations of

Table 1
Technical analysis summary.

Potential areas	Location	Power PV (kWp)	PV electricity yield (kWh kWp^{-1} year^{-1})
Area 1 (southern campus)	A4 building	101	1526
	Southern parking lot	367	1379
Area 2 (northern campus)	D-2 building	55	1509
	D-3 building	91	1531
	Northern parking lot	398	1391
Area 4 (sport facilities)	Soccer field pergola	110	1503
	Pitch	40	1489
		69	1497
	Sports hall Roof	74	1439



Fig. 5. PV integration on top of the A4 roof building.

Bing™.

the electricity company, as it could only be possible to install up to 220 kWp (two systems of 100 kW of inverter's power) because of legal constrains. The roof of the sports hall and the integration of a 113 m × 4 m PV pergola are the candidates for each of the systems, although we have included all the possible systems in order to widen up our economic and cost research.

The parking lot of Area 1, which is partially dedicated to the UNIVER project [10], has a large remaining extension to install additional PV modules, up to 367 kWp. Another intervention in this area is the one designed on the roof of building A4, where it can be installed perfectly oriented and tilted about 100 kWp (Fig. 5).

It is necessary to highlight that the buildings and parking lots located in Area 2 has been analyzed in energy terms but they have been rejected for the economic and cost analysis mainly because in order to inject the energy to high-voltage it is necessary the creation of a new transformer station. The extra elements for its construction and the bureaucracy of the local and national administration will give extra complexity to the research presented in this paper and it is out of the scope of our research.

3. Economic and cost analysis

Once it has been done the technical analysis, it is suitable to undertake the proper economic and cost analysis in each case identified in the previous section in order to get information about the economic profitability of the PVGCS on buildings, and additionally to calculate the electricity cost production of the life-cycle of the systems studied.

3.1. Calculation methods

The methods for the economic analysis used in this section are the net present value (*NPV*), the discounted payback time (*DPBT*) and the net internal rate of return (IRR_n). Some expressions, as well as definitions used to calculate the *NPV*, *DPBT*, and IRR_n in our work, will be shown hereafter.

The net present value (*NPV*, in €) of an investment project is the sum of present values of all cash inflows and outflows related to the investment [11]. Therefore, the parameter *NPV* equals the present worth of the cash inflows from the system ($PW[CIF(N)]$) minus the life-cycle cost from the user standpoint (LCC_{USP}). Thus it can be written, in general, as follows:

$$NPV = PW[CIF(N)] - LCC_{USP} \tag{1}$$

The *NPV* provides us the total net profit updated to the initial moment. Obviously, a PVGCS should be viewed favourably if $NPV > 0$.

The present worth of the cash inflows from the system may be written:

$$PW[CIF(N)] = p_u \times E_{PV} \times \frac{K_{PU}(1-K_{PU}^N)}{1-K_{PU}} \tag{2}$$

where p_u is the average unitary price per kWh to be paid to (which means selling PV electricity) or saved by the owner (€ kWh^{-1}),which means PV electricity consumption. E_{PV} is the annual PV electricity generated; N is the life of the PVGCS (years) and K_{PU}, which is a parameter used to simplify the previous equation, can be expressed as follows:

$$K_{PU} = \frac{1+\varepsilon_{pu}}{1+d} \tag{3}$$

where d is the nominal discount rate and the factor ε_{pu} is the annual increase rate of the PV electricity unitary price paid to or saved by the owner. The actual discount rate (d_a) is derived from the nominal discount rate by applying the following:

$$d_a = \frac{d-g}{1+g} \tag{4}$$

where g is the annual inflation rate.

In the net present value expression (Eq. (1)), the parameter LCC_{USP} is the sum of the present worth of the initial user investment of the photovoltaic system ($PW[PV_{UIN}]$, in €) plus the present worth of the operation and maintenance cost ($PW[PV_{OM}]$, in €):

$$LCC_{USP} = PW[PV_{UIN}] + PW[PV_{OM}] \tag{5}$$

In order to calculate the initial investment of the PV system it is suitable to define some parameters. Firstly, it is considered that PV_{IN} (€) is the initial investment on the photovoltaic system, while PV_{IS} (€) is stated as the initial investment subsidy, therefore $PV_{IN} - PV_{IS}$ is the quantity to be paid by the owner. However, this amount may be financed partially with a low-interest loan while the rest is financed by using the capital of the owner. This means that part of this amount is borrowed at an annual loan interest i_l and loan term N_l (years), while the remaining part of this amount is financed with own capital, so that the annual retribution for the own capital is given in form of dividends (d_i) and amortized at the end of the life-cycle of the system.

If PV_{OC} (€) is the portion of the initial investment financed with own capital, the present worth of the initial user investment of the photovoltaic system $PW[PV_{UIN}]$ can be written as

$$PW[PV_{UIN}] = \left((PV_{IN} - PV_{IS} - PV_{OC}) \times i_l \times \frac{(1+i_l)^{N_l}}{(1+i_l)^{N_l}-1} \times \frac{q(1-q^N)}{1-q}\right) + \left((d_i \times PV_{OC}) \times \frac{q(1-q^N)}{1-q} + PV_{OC}\right) \tag{6}$$

where the factor q is related with the discount rate:

$$q = \frac{1}{1+d} \tag{7}$$

Concerning to the present worth of the operation and maintenance cost $PW[PV_{OM}]$, it can be calculated using the following expression:

$$PW[PV_{OM}] = \left(PV_{AOM} \times \frac{K_{PV}(1-K_{PV}^{N})}{1-K_{PV}} \right) \quad (8)$$

where PV_{AOM} is the annual operation and maintenance cost and it is equal to 0.01 PV_{IN} [12]. K_{PV} is calculated by:

$$K_{PV} = \frac{1+\varepsilon_{PVOM}}{1+d} \quad (9)$$

where the factor ε_{PVOM} is the annual escalation rate of the operation and maintenance cost of the PV system.

Then, the net present value (*NPV*) may be re-written, bearing in mind Eq. (1), as follows:

$$NPV = PW[CIF(N)] - PW[PV_{UIN}] - PW[PV_{OM}] \quad (10)$$

The payback time of a project (more properly, the discounted payback time, *DPBT*) is the required number of years (PB) for the present worth of the inflows to equal the present worth of the outflows. Obviously, profitability means that the discounted payback time should not exceed the service life of the photovoltaic system ($DPBT < N$). Although easily understandable and straightforward, this parameter does not consider the cash flows that are produced after the *DPBT*. Hence, it might hide sound financial opportunities for those deciding to invest on a PV system [13].

The expression used to calculate the years of the discounted payback time is:

$$PW[CIF(PB)] \geq LCC_{USP}(PB) \quad (11)$$

Another method used in the economical analysis is the *internal rate of return* (*IRR*). The meaning of the *IRR* in an investment project is the value of the discount rate that leads to $NPV = 0$. According to Eq. (1), this means:

$$NPV = PW[CIF(N)] - LCC_{USP} = 0 \quad (12)$$

For a given project, the *IRR* equals the actual interest rate at which the project initial investment should be lent during its useful life to achieve the same profitability [14]. From an economic point of view, the PV system should be accepted if the *IRR* exceeds a profitability threshold fixed by the future owner. In this sense, this parameter is very important for the investor since it provides a meaningful estimation of the return of its investment.

The *net* internal rate of return (IRR_n), is the value of d_a that makes $NPV = 0$:

$$0 = PW[CIF(N)] - PW[PV_{UIN}] - PW[PV_{OM}] \quad (13)$$

The internal rate of return (*IRR*) is derived from the net *IRR* by using the formula:

$$IRR = IRR_n + WACC \quad (14)$$

where the weighted average cost of capital (*WACC*) refers to the cost that the owner of the PVGCS must pay for using the available financial resources to finance the initial investment.

In this paper, the net internal rate of return has been used because it provides the owner or investor with a net measure of the return of the investment. In other words, IRR_n derived from Eq. (13) takes into account the *WACC* to finance the initial investment.

Any PVGCS is economically feasible, from a profitability point of view, when the following circumstances occur: $NPV > 0$ and $IRR_n > WACC$.

Regarding the cost analysis done, it has been focused on the estimation of the electricity cost production through the concept: *levelised cost of electricity* (*LCOE*), or levelised electricity cost (*LEC*) depending on some authors, which can be defined as the cost, in current monetary units, of a unit of electricity produced by a given system [15]. This cost is levelised in real money and is constant over the whole lifetime of the system.

The essential economic concept for the photovoltaic grid-connected systems is that its cost should be recovered by the useful energy it produces over its life time, the levelised cost of electricity can be estimated taking into account the cumulate system costs divided by the energy produced over its lifetime, as it is shown in the following equation:

$$LCOE = \frac{LCC_{USP}}{\sum_{n=1}^{N} E_{PV}/(1+d)^n} \quad (15)$$

This factor that can be used to compare PV technology with other energy sources, both renewable and conventional.

3.2. Calculation of parameters

A review of some typical figures for the parameters that are involved in the calculation of the IRR_n, *NPV*, *DPBT* and LCOE will be carried out in this section. This review will lead to state the value of the parameters for each location of the PV systems described in the technical analysis.

The first parameter needed for the calculations of the previous section is the annual PV electricity yield (*Y*), has been obtained in the technical analysis section (see Table 1), taking into account that the most usual configuration of the BIPV is fixed flat-plate module.

According to the economic parameters described in Section 3.1, the representative initial investments (PV_{IN}) per kWp in PV grid-connected systems are shown in Table 2 for different European countries [16]. It is outstanding that in 2009 a decrease cost ranging from 20 to 40% was undergone when compared to 2008 [17–20]

Regarding the PV electricity unitary price per kWh (p_u), this parameter is fixed by the Spanish Decree RD1565/2010, where it sets a value of 0.2037 € kWh^{-1} for PVGCS installed on buildings. Apart from the unitary price, the annual increase rate of the PV electricity unitary price (ε_{pu}) paid to the owner is fixed by the Spanish Royal Decree 661/2007. According to the text, ε_{pu} is equal to the inflation rate (*g*) minus 0.5 point, so reviewing the averages of historical data for Spain in the period [21], it can be assumed a value for the inflation rate of $g = 3.3\%$, therefore, the annual increase rate can reach a value of $\varepsilon_{pu} = 2.8\%$.

In the case of the initial investment subsidy (PV_{IS}), some countries provide capital subsidies ranging from 10 to 50% of the initial investment [22], but this is not available in Spain any longer, so in our research PV_{IS} is assumed equal to 0%. Consequently, the initial investment (PV_{IN}) has to be paid by the owner.

This amount may be financed with low-interest loans or mixed financing, composed of a low-interest loan and own capital, which it is the option considered in this paper. It has been assumed that 80% of this amount is borrowed at an annual loan interest i_l and loan

Table 2
Indicative installed PVGCS prices per Wp in various countries in 2009.

Country	PVGCS < 10 kW (€ kWp^{-1})	PVGCS > 10 kW (€ kWp^{-1}
Austria	4.0–5.6	3.4–5.6
Denmark	2.7–5.4	2.7–6.7
Germany	3.0–4.3	2.8–3.8
France	5.0–5.5	2.5–4.5
UK	6.5–7.2	6.3–7.1
Italy	4.0–5.0	3.0–4.5
Norway	6.8–9.1	–
Portugal	5.0–6.0	4.0–5.0
Spain	3.2–4.6	3.0–4.3
Sweden	7.1	4.4

Ref. [16].
Note: Tracking, VAT and sales taxes excluded.

Table 3
Assumed values for each parameter in the different locations.

Potential areas	Location	Parameters						
		$[PV_{IN}]_{kWp}$ (€ kWp^{-1})	p_u (€ kWh^{-1})	ε_{pu} (%)	Low-interest loan		d_i (%)	δ (%)
					i_l (%)	N_l (years)		
Area 1 (southern campus)	A4 building	2600	0.2037	2.8	4	15	4	30
	Southern parking lot	2500						
Area 4 (sport facilities)	Soccer field pergola	2600						
	Pitch	2600						
		2600						
	Sports hall Roof	2600						

term N_l. The remaining investment amount, 20%, is contributed with own capital (PV_{OC}), so that the annual retribution is given in form of dividends (d_i) and amortized at the end of the life-cycle of the system. The values considered for the financial analysis are: annual loan interest $i_l = 4\%$, the loan term $N_l = 15$ years, and the dividends rate is assumed $d_i = 4\%$ [16,21].

There are different taxation systems according to the regulations of each country. Several tax coefficient (δ) values, ranging from 0% up to 40%, may be found in the literature [23]. In order to estimate the taxes, this coefficient has been applied to the cash inflow from the PVGCS, once the current asset amortization, the interest payments of the loan, and the operation and maintenance cost of the PVGCS are deducted. The asset amortization has been considered linear over the life cycle of the PVGCS and it has been excluded from taxation as mentioned above. The value tax coefficient is assumed to be $\delta = 30\%$.

To summarise the previous analysis, the figures chosen and assumed for every factor that define each photovoltaic system are gathered in Table 3.

Others assumptions have been made in our calculations:

- The serviceable life of the system (N) is always assumed equal to 25 years.
- The annual PV electricity yield generated by the system is assumed to decrease every year by 0.8% [11].
- The nominal discount rate (d) is assumed equal to the *WACC* in order to calculate the *LCOE*. This *WACC* will vary depending on how the financial resources are chosen to finance the initial investment. In our case the *WACC* is equal to 3.26%.
- Annual escalation rate of the operation and maintenance cost (ε_{PVOM}) is assumed equal to the value of the annual inflation rate 3.3%.

Solving the equations presented in Section 3.1 together with the figures shown in Tables 2 and 3, it has been estimated the *IRR*, IRR_n, *NPV*, *DPBT* and *LCOE* for each PVGCS considered.

3.3. Sensitivity analysis

Previous sensitivity analysis of the parameters studied above, such as *NPV*, *DPBT* and *IRR*, made by different authors [24], show that the variation of some factors involved in the energy generation such as the annual PV electricity yield, as well as some financial parameters like PV electricity unitary price, initial investment or the discount rate, can have a great impact in the effect of *NPV*, *DPBT* and *IRR* values.

In order to demonstrate the influence on the *LCOE* caused by possible changes in the value of some of the factors mentioned above (PV_{IN}, E_{PV} and d), a sensitivity analysis has been made in the possible PV system located in the A4 building (Area 1, Southern Campus). In this scenario, it has been defined a base case, with the parameters shown in Tables 1 and 3. This base case is the starting point for studying the deviations of the *LCOE* as function of the variations in the values of the factors that define this base case. Then, an analysis concerning the sensitivity of the PVGCS levelised cost of electricity for this scenario will be carried out, following the way that has been paved by some valuable contributions in similar fields [25,26].

4. Results and conclusions

Future owners and potential investors of PV grid-connected systems demand valuable information about the profitability of their investment, so the aim of this document if to provide information about the main profitability indexes of PV systems integrated on buildings.

The economic and cost results obtained in the studies are collected in Table 4, where it is shown a summary of the main profitability indices and the electricity cost production to the life-cycle of each of the PV systems installed in the locations analyzed.

The results obtained in this economic analysis recommend the implementation of PVGCS as its internal rate of return ranges from 5.57 to 6.21%, the net internal rate of return ranges from 2.31 to 2.95%, it has a positive net present value and the discounted payback time ranges from 16 to 17 years, under the economic scenario considered.

According to the cost analysis, the results of the LCOE parameter show that the price per kWh produced with photovoltaic solar energy is between 0.1301 and 0.141 € kWh^{-1} for the PV systems and scenario proposed in this research, so it is clear that electricity generated with PV sources will soon reach a competitive value.

In the case of the sensitivity analysis carried out in a specific building (A4, southern location), it is outstanding the influence that some parameters have on the LCOE for this technology. For example, a decrease in the initial investment is proportional with a cheaper LCOE as it is shown in Fig. 6. According to recent economic

Table 4
Economic analysis results.

Location	*NPV* (€)	IRR_n (%)	*IRR* (%)	*DPBT* (years)	*LCOE* (€/kWh)
A4 building	86,244	2.95	6.21	16	0.1301
Southern parking lot	232,644	2.31	5.57	17	0.1410
Soccer field pergola	88,567	2.79	6.05	16	0.1310
Pitch	31,019	2.69	5.95	16	0.1320
	54,678	2.75	6.01	16	0.1308
Sports hall roof	49,544	2.34	5.60	17	0.1385

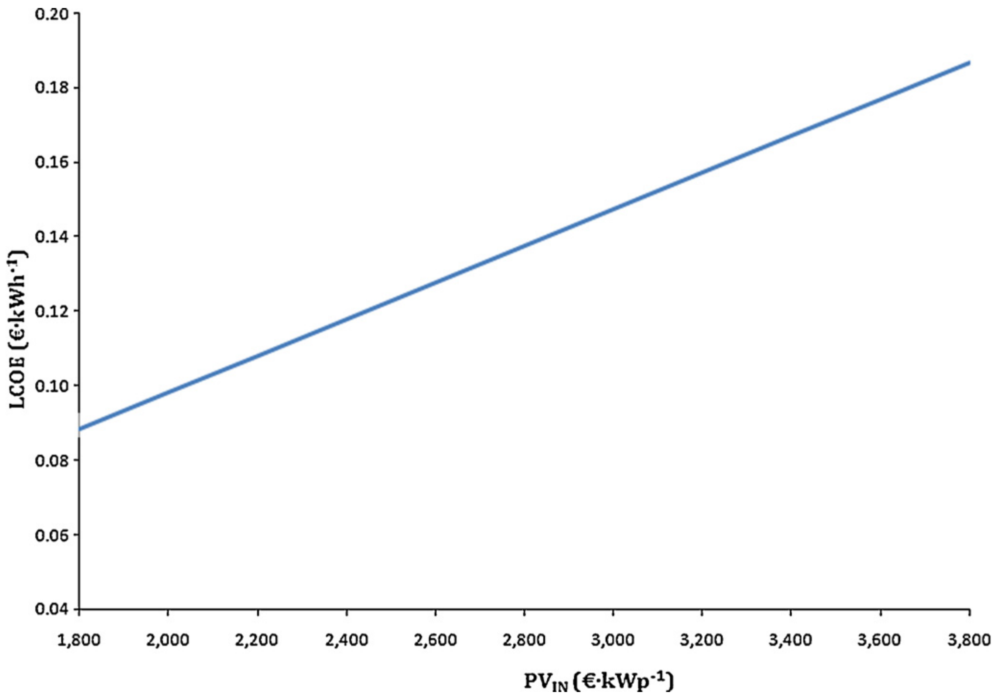


Fig. 6. Evolution of the LCOE considering different initial investments.

data [27], the decrease in PV module prices could set a positive trend in lowering the LCOE for this technology.

Fig. 7 is directly related with the PV technology used as well as it optimal inclination and orientation. If the energy yield of a PV system is higher, it means that LCOE can lower down exponentially, so this analysis stands for a right and proper installation of PV systems, using the most efficient modules and balance of system devices.

To conclude with the sensitive case analysis, Fig. 8 has been inserted in order to cover all the possible scenarios that the present unstable economic situation can cause in potential investments in this technology. Variations of the nominal discount rate of 5% (from $d = 2\%$ to $d = 7\%$) cause that the LCOE goes from 0.12 € kWh^{-1} to 0.18 € kWh^{-1} in the worst case analyzed.

According to the LCOE results obtained and taking into account the trend described in this section, the energy generated by means of photovoltaic technology can compete in the short-midterm with respect to other sources of energy, considering the economic and geographical scenario proposed in this paper.

Apart from the economic results and cost analysis, the tools shown in Section 2 can settle the basement of a more complex software tool useful to calculate the photovoltaic potential of a defined area.

The use of aerial pictures combined with advanced cartographic tools, such as the orthopicture, can offer a realistic vision of suitable locations for the PV systems integration, without the necessity of being physically in the chosen place.

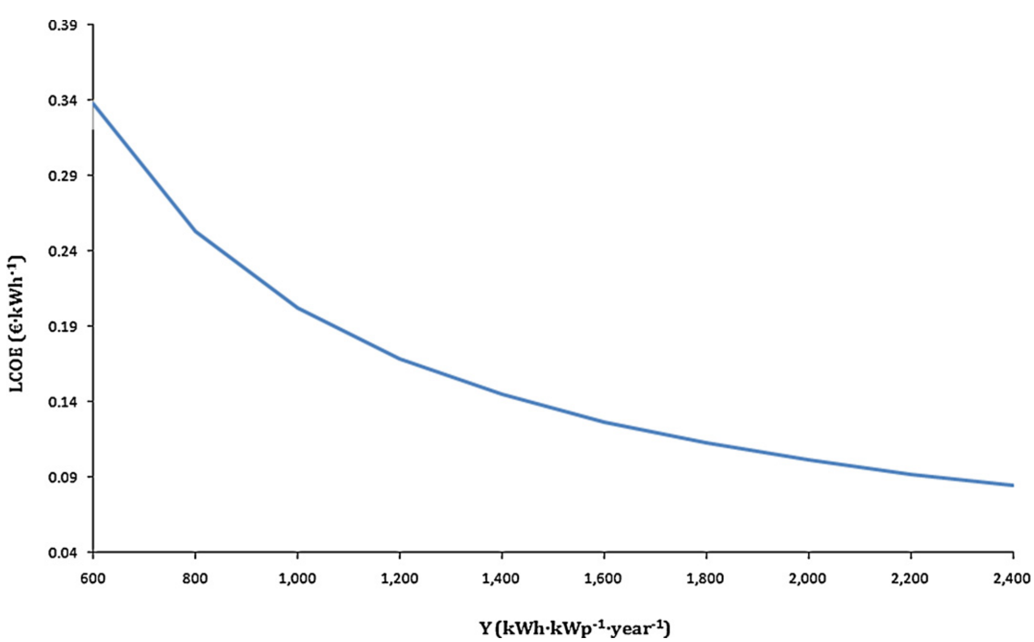


Fig. 7. Dependence of the LCOE with the energy yield of the system.

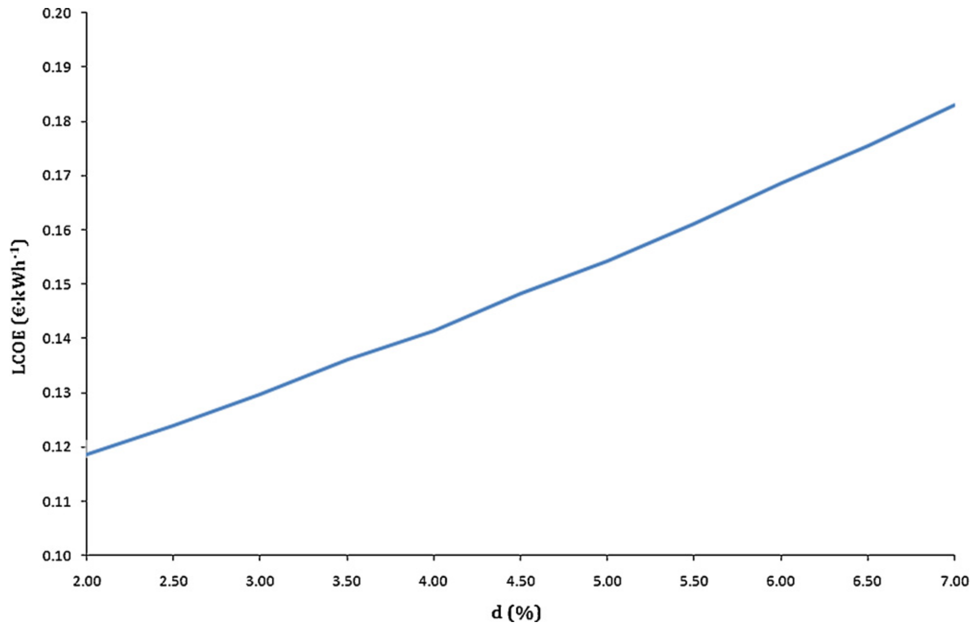


Fig. 8. Nominal discount rate influence in the LCOE.

Moreover, the combination of cartographic tools with commercial software such as PV-Syst can be further develop to build a more powerful tool that will be able to simulate and accurate calculate the energy generated by a possible PV system without being in the place or reducing to the minimum the traveling expenses for the recognition of the location.

Acknowledgements

This work was supported by the University of Jaén within the frame of the Projects: "UNIVERSOL" and "Análisis de sensibilidad de los principales parámetros tecnicos-económicos de los sistemas fotovoltaicos conectados a la red y su efecto sobre la rentabilidad de los mismos" under expedient code UJA_08_16_26, both funded by the University of Jaén.

The Center of Advanced studies in Energy and Environment has also been involved in the research presented in this paper, so we appreciate the job that the researchers of this Center have been carried out, as it has been very helpful.

Additionally, this research has been partially carried out thanks to the College Teacher Training Program (Formación de Profesorado Universitario) of the Spanish Ministry of Education

Appendix A. Terminology

d	Nominal discount rate.
d_a	Actual discount rate.
d_i	Dividends rate (annual retribution rate for own capital).
$DPBT$	Discounted payback time (years).
E_{PV}	Annual PV electricity generated (kWh year^{-1}).
g	Annual inflation rate.
i_l	Annual loan interest.
IRR	Internal rate of return.
IRR_n	Net internal rate of return.
K_{PV}	$(1+\varepsilon_{PVOM})/(1+d)$.
K_{PU}	$(1+\varepsilon_{pu})/(1+d)$.
LCC_{USP}	Life-cycle cost of the PVGCS from the user standpoint (€).
$LCOE$	Levelised cost of electricity (€ kWh^{-1})
N	Useful life of the PVGCS (years).
N_l	Time duration of loan (years).
NPV	Net present value (€).
PB	Number of years used for the DPBT.
p_u	PV-electricity unitary price paid to/saved by the user (€ kWh^{-1}).
PV_{AOM}	Annual operation and maintenance cost of the PVGCS (€).
PV_{IS}	Initial investment subsidy (€).
PV_{IN}	Initial investment on the PVGCS (€).
PV_{OC}	Initial investment financed with own capital) (€).
$PVGCS$	Photovoltaic grid-connected system.
$PW[CIF(N)]$	Present worth of the cash inflows from a PVGCS through its useful life (€).
$PW[PV_{OM}]$	Present worth of the PVGCS operation and maintenance cost (€).
$PW[PV_{UIN}]$	Present worth of the user initial investment on the PVGCS (€).
q	$1/(1+d)$.
$WACC$	Weighted average cost of capital.
Y	Annual electricity yield (kWh kWp^{-1} year^{-1}).
ε_{pu}	Annual increase rate of the energy price consumed/sold from/to the grid.
ε_{PVOM}	Annual escalation rate of the operation and maintenance cost of the PVGCS.

References

[1] Sick F, Erge T. Photovoltaics in buildings. London: James and James Ltd.; 1996.
[2] Chivelet NM, Fernández I. La envolvente Fotovoltaica en la arquitectura. Barcelona, Spain: Reverté; 2007.
[3] Royal Decree 1578/2008. Ministry of Industry, Tourism and Trade, Spain; September 26, 2008.
[4] Royal Decree 661/2007. Ministry of Industry, Tourism and Trade, Spain; May 25, 2007.
[5] Royal Decree 1565/2010. Ministry of Industry, Tourism and Trade, Spain; November 19, 2010.
[6] Ministry of Industry, Tourism and Trade, Spain, www.mityc.es/ENERGIA/ELECTRICIDAD/REGIMENESPECIAL/Paginas/InstalacionesFotovoltaicas.aspx [accessed April, 2011].
[7] Royal Decree Law 14/2010. Ministry of Industry, Tourism and Trade, Spain; December 23, 2010.
[8] Royal Decree 314/2006. Ministry of Housing, Spain; March 17, 2006.
[9] EC. Directive on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. 2009/28/EC; April 23, 2009. Available online from: www.energy.eu/directives/pro-re.pdf [accessed April, 2011].
[10] Almonacid G, Aguilera J, Perez PJ, Vidal PG. Univer project: a 200 kWp photovoltaic generator integrated at Jaén University campus. In: Proceedings of the 2nd world conference and exhibition on PV solar energy conversion conference. 1998. p. 2833–6.
[11] Lasnier F, Ang T. Photovoltaic engineering handbook. Great Yarmouth: Adam Hilger; 1990. p. 371–399.
[12] Danchev S, Maniatis G, Tsakanikas A. Returns on investment in electricity producing photovoltaic systems under de-escalating feed-in tariffs: The case of Greece. Renewable and Sustainable Energy Reviews 2010;14:500–5.
[13] Perez R, Burtis L, Hoff T, Swanson S, Herig C. Quantifying residential PV economics in the US-payback vs cash flow determination of fair energy value. Solar Energy 2004;77:363–6.

[14] Chabot B. From cost to prices: economic analysis of photovoltaic energy and services. Progress in Photovoltaics: Research and Applications 1998;6:55–68.
[15] Short W, Packey DJ, Holt T. A manual for the economic evaluation of energy efficiency and renewable energy technologies. NREL/TP-462-5173. Golden, Colorado: NREL; 1995.
[16] IEA. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2009, report IEA-PVPS T1-19; 2010. Available online from: www.iea-pvps.org/index.php?id=92 [accessed April, 2011].
[17] IEA. National survey report of PV power applications in Italia 2009. IEA, photovoltaic power systems programme; May, 2010. Available online from: www.iea-pvps.org/index.php?id=93 [accessed April, 2011].
[18] IEA. National survey report of PV power applications in Japan 2009. IEA, photovoltaic power systems programme; May 2010. Available online from: www.iea-pvps.org/index.php?id=93 [accessed April 2011].
[19] IEA. The photovoltaic sector in France year 2009. IEA; May 2010. Available online from: www.iea-pvps.org/index.php?id=93 [accessed April 2011].
[20] REN21, 2010. Renewable, Global status report. Renewable Energy Policy Network for the 21st Century. Available online from: www.ren21.net/Portals/97/documents/GSR/REN21_GSR_2010_full_revised%20Sept2010.pdf [accessed April 2011].
[21] ECB. Statistics pocket book; July 2010. European Central Bank; 2010. Available online from: www.ecb.int/pub/pdf/stapobo/spb201007en.pdf [accessed April, 2011].
[22] REN21. Renewables: global status report, 2009 update. REN21 renewable energy policy network; 2009. Available online from: www.ren21.net/Portals/97/documents/GSR/RE_GSR_2009_Update.pdf [accessed April, 2011].
[23] Kaldellis JK, Vlachou DS, Korbakis G. Techno-economic evaluation of small hydro power plants in Greece: a complete sensitivity analysis. Energy Policy 2005;33:1969–85.
[24] Talavera DL, Nofuentes G, Aguilera J. The internal rate of return of photovoltaic grid-connected systems: a comprehensive sensitivity analysis. Renewable Energy 2010;35:101–11.
[25] EPIA. Set for 2020. Solar photovoltaic electricity: a mainstream power source in Europe by 2020. European Photovoltaic Industry Association; 2009 p. 44–46. Available online from: www.setfor2020.eu/ [accessed April, 2011].
[26] EPIA. Potential of on-grid photovoltaic solar energy in sunbelt countries. Executive summary; December 2009. Available online from: www.solarcop16.org/uploads/Potential%20of%20On-Grid%20PV%20in%20Sunbelt%20Countries,%20executive%20summary,%20final.pdf [accessed April, 2011].
[27] Photon International. Beate Knoll. Downward path. Photon International; January 2011. p. 106–113.